Multidisciplinary Analysis of a Hypersonic Engine

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Abstract

This paper describes implementation of a technique used to obtain a high fidelity fluid-thermal-structural solution of a combined cycle engine at its scram design point. Single-discipline simulations are insufficient here since interactions from other disciplines are significant. Using off-the-shelf, validated solvers for the fluid, chemistry, thermal, and structural solutions, this approach couples together their results to obtain consistent solutions.

Introduction

To reduce the cost of access to space, NASA has focused on several propulsion concepts. In one longer-term view, the ISTAR program is examining the Rocket Based Combined Cycle [1,2,3] (RBCC) concept that integrates a rocket and a ram/scram jet. In particular, the low speed and ex-atmospheric advantages of rocket propulsion are combined with the higher specific impulse of air breathing propulsion to obtain a more efficient propulsion system. A concept design analyzed here is a strutjet engine that alternates rocket containing struts with combustor ducts as indicated in Figure 1.

Particularly with high fidelity analysis, a common design practice is to neglect some multidisciplinary interactions. While this practice is adequate in many instances, a successful RBCC design is a careful balance between aerodynamics, combustion, thermal management, structural and weight requirements. Consistent multidisciplinary solutions should capture these interactions, identify their consequences, and consequently play a role in design.

The techniques implemented here apply not only to RBCC designs but to a range of problems where multidisciplinary interactions are significant. In particular, these techniques may be readily applied to TBCC designs. A long term goal of this work is developing a toolkit that simplifies the multidisciplinary coupling of off-the-shelf codes.

The following sections present the three component simulations, details of the coupling of these simulations, important coupling issues, results, and a discussion of the added cost of multidisciplinary analysis.

Component Simulations

The present work involves three steady, three-dimensional simulations for ISTAR engine components: a fluid simulation of the approach flow over the vehicle forebody and engine duct inlet, a fluid-chemistry simulation for the combustor, and a thermal-structural simulation of the engine walls.

Vehicle Forebody and Engine Inlet:
The hypersonic approach flow over the vehicle forebody and into the engine inlet is calculated at the scram design point with the Navier-Stokes code, OVERFLOW [4]. A κ-ω turbulence model is used with boundary layer grid resolution of $y^+ \sim 1$ (at the first node off the wall) [4,5]. OVERFLOW modifications allow simulation of equilibrium chemistry air. All vehicle surfaces that can influence the engine inlet airflow are included in a Chimera (overlapping)

Figure 1: ISTAR Vehicle concept and Strutjet Engine [1] (side and front views)
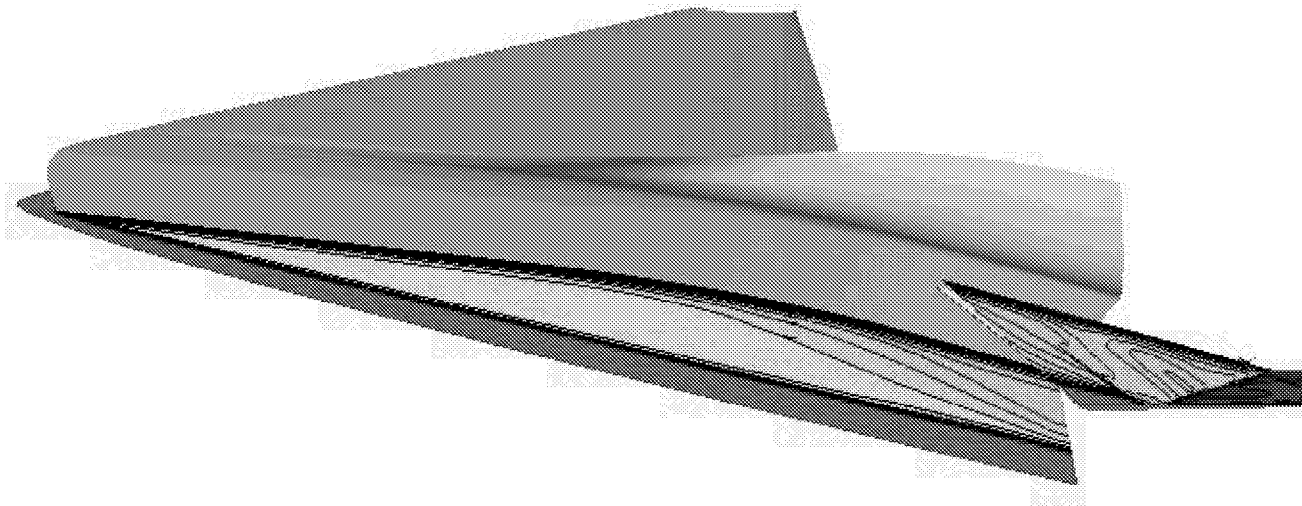

Figure 2: Approach flow Mach contours along the symmetry surfaces of the vehicle forebody and one engine strut-to-strut flowpath.

structured grid system (5 blocks; 9×10^5 cells) generated with GRIDGEN [6]. Here, Chimera grids simplify complex geometry grid generation, and accommodate some design changes. Interpolation quantities for this Chimera grid system are calculated with PEGASUS [7]. Centerline symmetry is assumed for both the vehicle and the single strut-to-strut flow path simulated. Wall temperatures must be specified—initially a guess and on subsequent cycles temperatures are interpolated from the solid's thermal-structural model. The forebody/inlet configuration and an approach flow solution are shown in Figure 2.

Combustor Fluid-Chemistry Analysis:
Scram combustion within the engine is simulated using the Navier-Stokes plus finite rate chemistry code, VULCAN [8]. A κ-ω turbulence model with wall-functions is used with grid resolution of the boundary

layer to $y^+_{max} < 500$. Radiation effects are not included. The combustor inflow is supersonic and calculated from the approach solution by interpolating solution quantities between grids.

Within the engine, the cascade fuel injectors are modeled as single triangular slots with area, mass flow, and momentum equal to the actual injectors. Combustion is simulated with a 6-species, 3-step finite-rate Ethylene model. Although it was not part of the preliminary CAD model, a flame holding cavity was added to facilitate and sustain combustion. Wall temperatures must be specified—the initial value is a guess, and on subsequent cycles temperatures are interpolated from the thermal model. The grid contains five composite (non-overlapping) blocks (1.9×10^5 cells), and centerline symmetry is assumed. A typical combustor configuration and a solution are shown in Figure 3.
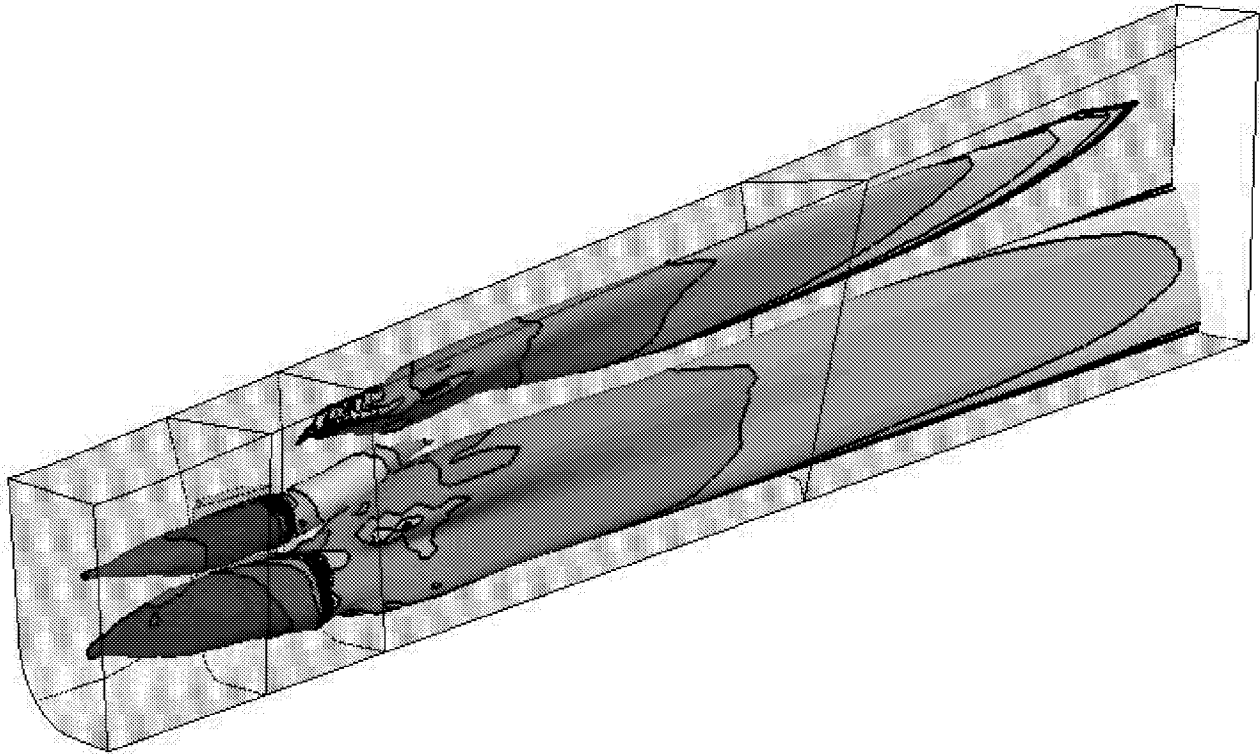
Figure 3: Combustor duct cutaway showing fuel mass fraction iso-surfaces colored by temperature. Centerline symmetry is assumed.

Engine Strut Thermal and Structural Analyses:

Both the thermal and structural simulations are performed individually using ANSYS [9], a commercially available finite element solver. From engine geometry CAD files, a three-dimensional, unstructured, tetrahedral thermal-structural mesh was created within ANSYS (1.3×10^5 nodes, 8.6×10^4 tetrahedra); shell elements, although simpler, cannot capture the normal heat conduction that is of interest here. Centerline symmetry was assumed.

Temperature-dependent material properties for Inconel 625 and Titanium β21S are taken from manufacturer's specifications [10,11]. A thermal barrier coating on the engine strut surface is modeled with homogenized material properties. Coolant passages are modeled by dividing the geometry into two-layers at coolant surfaces; the coolant temperature is applied at this bilayer surface (Figure 4). This model neglects details of heat conduction around each coolant passage.

Surface heat fluxes and pressures are calculated from the fluid solutions, interpolated onto this thermal-
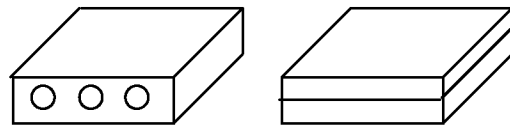

Figure 4: Coolant Passages (left) are modeled with a bilayer material (right); the coolant temperature is applied on the intermediate surface.

structural model, and used as boundary conditions in each ANSYS analysis. The coolant temperature boundary condition is specified in the thermal analysis as either a fixed temperature, or as a temperature distribution calculated after integrating the heat flux along each coolant channel. After the thermal analysis of this model, the resulting wall temperatures are interpolated onto the surfaces of the fluid grids and used as boundary conditions in the fluid calculations. Similarly, surface deflections from the structural analysis can be interpolated and used to deform the fluid grids. A typical thermal solution is shown in Figure 5, and a typical structural solution is shown in Figure 6.

Figure 5: Engine strut thermal model showing temperature contours for scram combustion. The five fuel-injectors are the small, dark triangular regions.
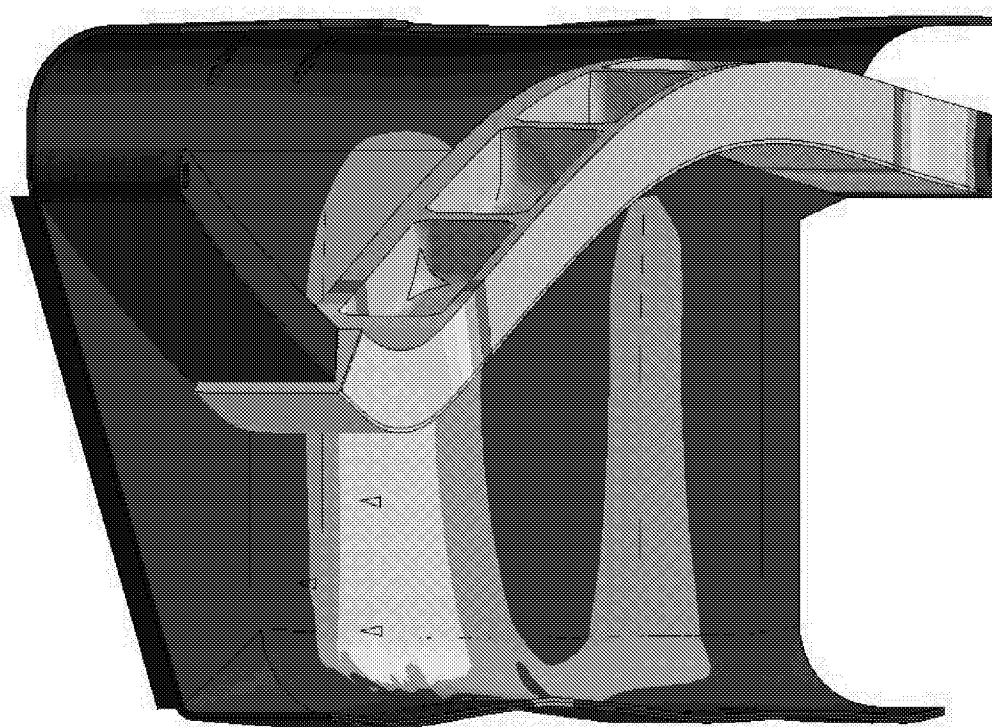

Figure 6: Engine strut structural model showing deflection contours at the scram design point. Deflections are exaggerated.

Coupling Procedures

The objective of coupling these three simulations together is to ensure a consistent solution for the engine: flow quantities are the same where the fluid codes meet, heat fluxes and temperatures are the same where fluid and thermal codes meet, and the deflected walls are the same as the fluid boundaries. Three coupling procedures are necessary here; between the inlet and combustor calculations there is a fluid-fluid coupling, and between the flowpath and the solid walls both a fluid-thermal and a fluid-structural coupling exist.

Fluid-Fluid Coupling

The inlet (OVERFLOW) and combustor (VULCAN) fluid calculations overlap near the throat, and coupling ensures that flow quantities are consistent there. Since the flow is supersonic and boundary layers are attached, the downstream influence is assumed to be negligible; outflow values of inlet solution variables are interpolated onto the combustor grid.

There are three interpolation challenges in this coupling. First, different codes may use different flow or turbulence variables, nondimensionalizations, and/or units; transformation of variables may be necessary. Here, κ-ω turbulence models were chosen in both calculations. However, for a faster turnaround time, wall-functions were chosen in VULCAN; OVERFLOW has only a low-Reynolds number (integration to wall) turbulence model. Second, the interpolation of ω was complicated by its singular behavior in boundary layers. Interpolation of the turbulent viscosity, $\rho\kappa/\omega$, was better behaved. Third, interpolation in the highly resolved boundary layer meshes near curved walls can be difficult. In Figure 7, discretely sampled points on one mesh (dashed line) can lie outside the other mesh (solid line); interpolation is not possible, and extrapolation from nearest neighbors is required.
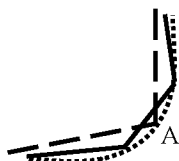

Figure 7: Interpolation between two discrete grids (solid and dashed lines) fails at point A on a curved boundary (dotted line). Extrapolation from nearest neighbors is required.

Fluid-Thermal Coupling

The correct thermal boundary condition is continuous heat fluxes and temperatures at the interface between fluid and thermal codes; however, calculating heat fluxes from a fluid solution and applying them in a thermal calculation, will not satisfy this condition, in general.

To obtain consistent thermal solutions, the current approach is to iterate between the fluid and thermal solvers [12,13,14]. Starting with a guess temperature for the fluid-solid interface, a fluid solution is obtained, interface heat fluxes are calculated and imposed on the thermal solver. The resulting thermal solution revises the interface temperature. This cycle continues to convergence, and in practical problems, this procedure converges within 10 iterations [12].

There are three challenges in this coupling. First, the convergence of this procedure is sensitive to several factors including material properties and the initial guess wall temperature. Some work has not required under-relaxation for convergence [12], while other researchers have used it [14,15]. In the current work, interface temperatures oscillated during the fluid-thermal iteration both for VULCAN and OVERFLOW. Under-relaxation ($w=0.25$–0.5) of the interface temperatures calculated by ANSYS allowed convergence. The appendix presents a theoretical analysis that predicts oscillations, sensitivity to the material thermal conductivities, and the need for under-relaxation to improve convergence. Convergence was also improved by using VULCAN's thermally mixed boundary condition to generate the initial guess temperature distribution. This boundary condition couples heat fluxes at the wall with a one-dimensional solid wall heat conduction analysis [15].

Second, the calculation of accurate heat fluxes is challenging [13] for OVERFLOW. The heat flux calculation involves a difference of flow variables (which decreases the order-of-accuracy) performed in the highly refined boundary layer grid. Any lack of smoothness in the grid contributes to noisy fluxes; the grid singular line in the rounded strut corner is a source of noise.

Third, the turbulence model has an influence on the wall heat fluxes. VULCAN uses wall-functions and a coarser boundary layer grid resolution. Here, the heat flux is calculated from a functional representation of

the boundary layer profile. In practice, VULCAN heat fluxes are less noisy. However, a debate exists about the relative accuracy of heat fluxes calculated from wall-function and low-Reynolds number turbulence models. Even in a geometrically simple test problem (Mach 3 flow across a constant temperature flat plate), heat flux predictions from VULCAN and OVERFLOW differ by 11 to 15 percent. Further, in the engine duct where the converged OVERFLOW and VULCAN fluid-thermal simulations overlap, the heat fluxes have disparate values.

Fluid-Structural Coupling

Like the fluid-thermal coupling, the correct fluid-structural interface condition is consistent pressures and deflections between fluid and structural codes. The common practice of neglecting surface deflections in the fluid simulations does not satisfy this condition, in general.

To find consistent structural solutions, pressures from the converged fluid-thermal simulations are interpolated onto the fluid-solid interface of the structural grid; these pressures are boundary conditions in the structural analysis. From the thermal analysis, the temperature distribution in the solid is used in the structural analysis. Deflections calculated in the structural analysis are interpolated back to the fluid grids and used to deform these grids. This cycle is continued to convergence.

There are two interpolation challenges in this coupling. First, the engine ramp and engine strut deflect independently, since they are not attached (Figure 8). Deformations are discontinuous across the wall-ramp gap, and the interpolation procedure must not confuse points on different components. Consequently, when searching for an interpolation stencil, a restriction is required: interpolation must be to the same engine component.
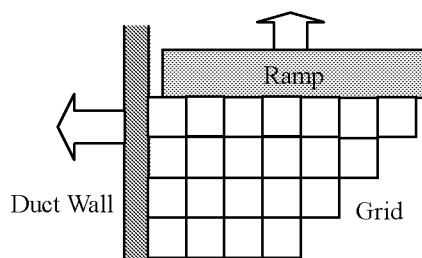

Figure 8: The engine ramp and strut deflect independently; interpolation must be to the same engine component.

Second, deforming fluid grids becomes difficult as deformations—particularly shear (tangent to wall) deformations—exceed the grid spacing. Since VULCAN uses wall functions, wall spacing is coarse and grid deformation is straightforward. OVERFLOW grids have finer wall spacing and must also be of sufficient quality for CHIMERA/PEGSUS interpolation. These two constraints present a challenge.

Results

Fluid—including combustion—(Figures 2, 3), thermal (Figure 5), and structural solutions (Figure 6) have been obtained for this ISTAR engine configuration at its scram design point. The fluid and thermal solutions have been converged so that temperatures and heat fluxes are consistent at the fluid-solid interface. The fluid and structural simulations have been iterated through one cycle.

The fluid-thermal iteration substantially changes the engine strut wall temperatures. The initial, uniform, wall temperature of the strut was taken to be 1560 °R for both OVERFLOW and VULCAN. The L2 norm, $(\Sigma (\Delta T)^2/N)^{1/2}$, of the temperature change, ΔT, between the initial and converged temperatures was 500 °R. The heat fluxes calculated before and after the fluid-thermal convergence are substantially different. As expected the qualitative details of the duct flow changed slightly.

These computational results reveal quantitative details of inlet performance, engine combustion, heat transfer-thermal management, and structural deflections and stresses. If these analyses were performed concurrently with the early design process, these results would have been valuable. These techniques compliment cycle analyses, and one- and two-dimensional computations, and help understand wind tunnel data and flight engine design. Also, these results can provide insights into design trade-offs. As with any CFD calculation, one must consider the limitations of the numerical methods, computational grid, and physical models.

The Cost of Multidisciplinary Analysis

The manual effort to setup and perfect single discipline simulations is substantial—on the order of months. This effort is dominated by the manual effort of structured, fluid grid generation. However, it is

important to distinguish the added cost of performing a multidisciplinary analysis—with these single discipline simulations in hand. This cost can be broken into two components: the additional computation time, and the setup time for the iterative coupling. While computation time approximately doubles, the increase in setup time is hard to quantify and may be reduced by a coupling toolkit.

Estimating the added computation time for a multidisciplinary simulation is also complicated by the disparate execution times of the component solvers. The thermal-structural model and interpolation require only minutes; while the fluid-combustion models require on the order of tens of hours. Some improvements may be possible. More aggressive parallel execution of the fluid solvers may reduce turnaround time. Further, in this preliminary work the fluid codes were completely converged within each fluid-thermal iteration; with such disparate time scales, this restriction may waste computational resources, especially in the initial iterations when large changes occur on the boundaries.

Setting up these multidisciplinary couplings involves working with file formats to output and input solution variables; transforming variables to correct for different units, nondimensionalizations, and even different solution variables; massaging files to identify and format interpolation surfaces; interpolating these variables between grids; and carefully overseeing the entire process. A goal of this work is automating these steps, where possible, and creating a general toolkit for coupling off-the-shelf simulation codes.

Implementation of this coupling procedure has revealed obstacles to achieving this goal. First, interpolation is challenging particularly in boundary layer meshes, at boundaries, and where components meet. Second, variable transformations are often unavoidable; different codes use different units and nondimensionalization of solution variables, (i.e. different turbulence models). Third, the calculation of heat fluxes is problematic. Fourth, when shear deformations are larger than grid spacing, deforming grids can be challenging.

Summary

This paper describes a procedure for obtaining consistent fluid-thermal-structural solutions. The procedure is intended to handle off-the-shelf, single-discipline solvers with limited or no access to solver source code. The procedure is used to analyze the scram design point of an air-breathing combined cycle engine. It is envisioned that the consistent multidisciplinary solution given by this procedure can aid in the engine's design, and be used for optimization of the design across all three disciplines.

Numerical experiments and theoretical analysis indicate that under-relaxation may be needed for convergence of the fluid-thermal iteration. Some researchers have used under-relaxation [14,15], while other work has not required it [12]. The following theoretical analysis provides guidance for converging fluid and thermal solutions to a consistent solution.

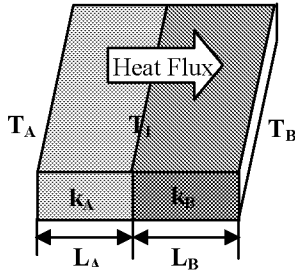For the simple geometry of Figure A, the analysis derives a single equation that reflects both the solution

Figure A: The bilayer solid contains materials A and B, with constant thermal conductivities k_A and k_B, and thickness L_A and L_B. The exterior surfaces are kept at constant temperatures T_A and T_B, defining a one-dimensional problem. The temperature, T_I, at the interface between A and B, is found with the same procedure as in the fluid-thermal iteration. Clearly, the problem of interest is a fluid-solid and not a solid-solid interface.

procedure and the transfer of heat fluxes and temperatures during a fluid-thermal iteration. The equation variable, ε^i, is the difference between the consistent interface temperature, T_I, and the calculated value after i iterations.

$$\varepsilon^i = -\alpha\,\varepsilon^{i-1}, \quad \text{where} \quad \alpha = (k_A L_B / k_B L_A) > 0$$

This result predicts that the iterated temperatures oscillate about the converged value, which we have observed. Further it predicts convergence is stable for $\alpha < 1$, which corresponds to high thermal conductivity for the solid in the fluid-thermal iteration. Again this result has been observed.

If we model the analogue of under-relaxing the interface temperatures calculated by ANSYS (parameter $0 < w \leq 1$), the equation becomes

$$\varepsilon^i = [\,1 - w\,(\,1 + \alpha\,)\,]\,\varepsilon^{i-1}$$

This result predicts that sufficient under-relaxation of the iterated interface temperatures will always yield convergence. In the fluid-thermal iteration, under-relaxation values, w, of 0.5 and 0.25 were necessary to converge the VULCAN-ANSYS and OVERFLOW-ANSYS iterations, respectively.

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